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Cosmic Infrared Background Experiment (CIBER): A Probe of Extragalactic Background Light from Reionization

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Abstract.
The Cosmic Infrared Background ExpeRiment (CIBER) is a rocket-borne absolute photometry imaging and spectroscopy experiment optimized to detect signatures of first-light galaxies present during reionization in the unresolved IR background. CIBER-I consists of a wide-field two-color camera for fluctuation measurements, a low-resolution absolute spectrometer for EBL measurements, and a narrow-band imaging spectrometer to measure and correct scattered emission from the foreground zodiacal cloud. CIBER-I was successfully flown on February 25th, 2009 and is expected to be flown three more times over the next two years at six month intervals. CIBER-II is a wide-field 30 cm imager operating in 4 bands between 0.5 and 2.1 microns. It is designed for a high sigma detection of unresolved IR background fluctuations at the minimum level necessary for reionization. With an etendue (a figure-of-merit for survey studies) a factor of 50 to 500 larger than existing IR instruments on satellites, CIBER-II will carry out the definitive study to establish the surface density of sources responsible for reionization.

INTRODUCTION

The optical and UV radiation from sources during reionization is now present in the near-infrared with a small, but non-negligible, contribution to the Extragalactic Background Light (EBL). Searches for this radiation based on absolute photometry have proven problematic due to confusion with the zodiacal foreground. Instead of the absolute background, in Cooray et al. (2004) we proposed the development of a near-infrared sounding rocket experiment, CIBER, to conduct a deep search for extragalactic background fluctuations from the epoch of reionization associated with first-light galaxies.

The EBL spectrum contains all radiative information from the reionization epoch (Santos et al. 2003; Kashlinsky et al. 2004; Fernandez & Komatsu 2006; Cooray et al. 2009). We expect that the EBL contains diffuse signatures of reionization, such as Ly-α background radiation redshifted to near-IR wavelengths today. Remnants of these first stars, black holes in the form of miniquasars, will also contribute to the EBL (Cooray &

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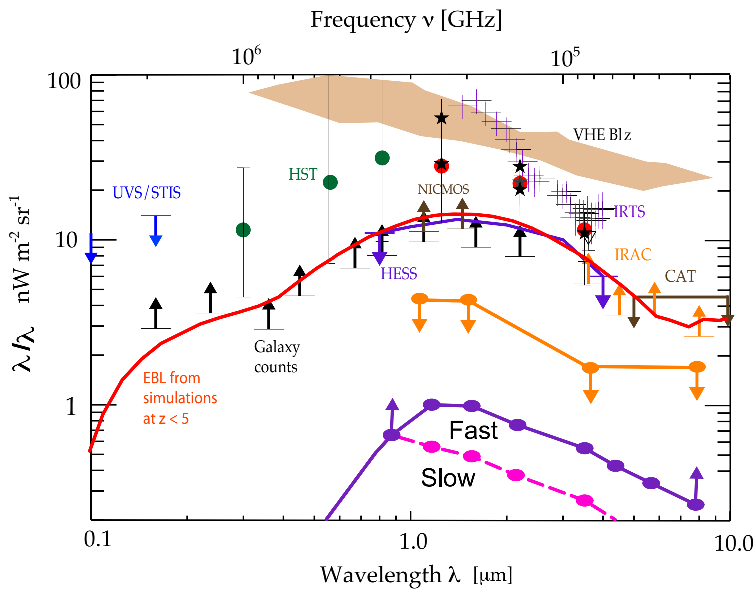

FIGURE 1. Summary of EBL observations at infrared and optical wavelengths, showing upper limits, reported residuals after subtraction of local foregrounds, reported detections with absolute photometry (DIRBE and IRTS), and integrated galaxy counts (lower limits). The large experimental scatter at 1.2 μm is notable, with zodiacal removal suspected as a prime source of systematic error (Dwek et al. 2005). A recent upper limit based on TeV absorption using HESS (Aharonian et al. 2006) contradicts the excess reported by several authors at 1-2 μm. The indirect EBL measurements with TeV spectra, however, do not provide consistent results since a previous independent estimate suggests a higher background (the region labeled VHE Blz; Schroedter 2005) . The red line shows the integrated galaxy light associated with galaxies formed at $z < 5$ based on a semi-analytical model (Primack et al. 2008). The purple and pink lower lines show the estimated EBL from $z > 6$ for fast and slow reionization histories, which are lower limits since the calculation is based on the minimum UV luminosity density needed to reionize and maintain the ionized state of the intergalactic medium (Chary & Cooray 2010). The orange upper limits show constraints on the first-light EBL from reported fluctuations in deep Spitzer and NICMOS images.

Yoshida 2004).

Interestingly, integrated individual galaxy counts appear to fall short of the EBL measured with absolute photometry at near-infrared wavelengths (Fig. 1). For instance, in the 1-3 μm band galaxies contribute an intensity of $\sim$10 nW m^{-2} sr^{-1} (Madau & Pozzetti 2000). In contrast, the extragalactic background light (EBL) measured by DIRBE and the IRTS at the same wavelengths ranges from 10 nW m^{-2} sr^{-1} at 3.6 μm (Levenson & Wright 2008) up to 60 nW m^{-2} sr^{-1} at 1.2 μm (Cambresy et al. 2001; Matsumoto et al. 2005). It is highly unlikely that the entire difference is due to sources during reionization, since such a large intensity places unphysical requirements on star formation (Madau & Silk 2005).

Although the total luminosity produced by sources responsible for reionization is uncertain, a lower limit can be established by assuming the minimal number of photons needed to produce and maintain reionization, given existing information on reionization, rest-frame UV luminosity functions of galaxies at $z > 6$, and stellar mass estimates for galaxies at $z \sim 6$, among others (Chary & Cooray 2010). Such minimal reionization scenarios produce an EBL $\sim$ 1 nW m^{-2} sr^{-1}, a level undetectable by current absolute photometry measurements which, after dedicated space-borne measurements, show large discrepancies. As the spectral signature in EBL from reionization contains integrated emission from all sources, including fainter ones undetectable with JWST, it captures the exact reionization history and provides more information than other known probes of reionization, including the CMB and 21-cm background. This spectral feature could be resolved in the future with absolute photometric measurements in narrow spectral bands between 1-2 μm with an out-of-zodi EBL explorer at distances around 5 AU (Cooray et al. 2009).

Even in the relatively recent times since reionization it appears there may be an under-accounting of galaxies. The current star-formation in Lyman-break galaxies (LBGs) at z $\sim$ 6 (Bouwens et al. 2006) falls by about a factor of 6 - 9 below the minimum required to maintain an ionized IGM, given canonical estimates for the clumping factor of the gas and the escape fraction of ionizing photons from galaxies. The upper limits on the ultraviolet luminosity function suggests a negative evolution with increasing redshift, in the sense that galaxies at the bright end of the UV luminosity function at z $\sim$ 6 were fainter in the ultraviolet at earlier times. The implication is that the contribution from star-formation in faint galaxies, below the detection threshold of current surveys, is higher than has been estimated. The *Spitzer* stellar mass estimates suggest a top-heavy IMF for high redshift galaxies (Chary 2008), suggesting a different stellar population in those galaxies than in the local Universe. If current galaxy surveys under-account for galaxy evolution or miss populations, the deficit may be uncovered in a careful study of the EBL.

A first-light galaxy EBL component from reionization and any contribution from faint sources at $z \sim 6$ unresolved by existing deep, pencil surveys can be uncovered using a careful study of background fluctuations (Cooray et al. 2004). The technique involves the measurement of the angular power spectrum via an anisotropy study, similar in method to well-established techniques for studying CMB anisotropy. First-light galaxies have predictable clustering, determined by the growth of dark matter perturbations in ΛCDM cosmology, and will produce EBL fluctuations with a characteristic spatial power spectrum. zodiacal light is known to be spatially uniform on arcminute scales. What is uncertain is the amplitude of fluctuations since it depends on the astrophysics of reionization and the importance of, for example, fainter sources at $z \sim 6$ to 8 that are responsible for maintaining reionization. A fluctuation measurement has the potential to detect a first-light galaxy component to the EBL at much fainter levels than can be probed with absolute photometry.

Since our work on CIBER began (Cooray et al. 2004; Bock et al. 2006), *Spitzer* IRAC data have been used to carry out studies of EBL clustering anisotropy. After a deep removal of point sources and deconvolving emission from the extended PSF, Kashlinsky et al. (2005; 2007) claim detection of first-light galaxy fluctuations based on a deviation from a shot-noise power spectrum on the largest angular scales.

Some doubt may be cast on the interpretation of first sources due to the angular scales and wavelengths covered by IRAC. Due to IRAC's small field of view, the

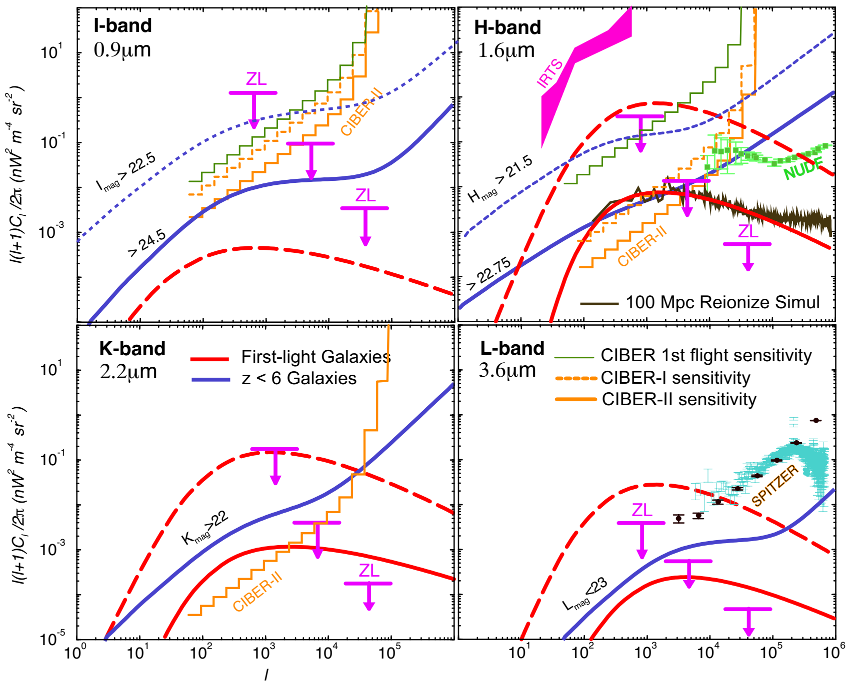

FIGURE 2. Spatial power spectrum of EBL fluctuations in standard IR bands. The red curves show the power spectra of fluctuations from first-light galaxies forming over the redshift interval $8 < z < 15$. The top red dashed line shows the case where fluctuations are normalized to *Spitzer* measurements (Kashlinsky et al. 2008). The bottom solid line shows the minimal signal necessary to produce reionization. Cyan points show *Spitzer* measurements by Kashlinsky et al. while black points show residuals from Cooray et al. after subtracting faint, blue dwarfs detected in deep HST ACS images. The dark blue curves give estimated fluctuations from known galaxies, as a function of magnitude cutoff, based on a galaxy distribution model based on the halo appoach (Cooray & Sheth 2002; Cooray 2006) matched to existing clustering data (e.g., Sullivan et al. 2007). The galaxy cutoff taken for CIBER is 25% pixel removal using deep ancillary source catalogs. CIBER-II (solid blue) has a lower residual local galaxy foreground due to its smaller pixel size compared with CIBER-I (dashed blue). The orange stair-steps in the three panels show the binned statistical sensitivity of CIBER-I and CIBER-II instruments in a single 50 s observation. The thin line shows the statistical sensitivity achieved in the first flight in February 2009. zodiacal light is known to be spatially uniform, shown by the upper limits. The black line shows the EBL fluctuations resulting from a 2048^3 particle, large volume (100 Mpc) numerical simulation of reionization completed by the Princeton group (Trac & Cen 2007) with a combination of both Pop II and Pop III stars in first-light galaxies, as analyzed by the UCI team. The shape of fluctuations is model independent and shows the overall bump at $\ell \sim 1000$ in agreement with the analytical model.

power spectrum from high-z objects must be carefully separated from fainter, unresolved foreground galaxies (Cooray et al. 2007; Chary et al. 2008). In addition, fluctuation measurements have been made at shorter near-IR wavelengths in narrow, but very deep, NICMOS images (Thompson et al. 2007). The images again show a fluctuation signal (Fig 2). The spectrum of fluctuations measured between *Spitzer* IRAC and HST NICMOS appears to be approximately flat, and the authors state it does not correspond to the shape expected for $z > 8$ sources (Thompson et al. 2007), but rather to a low-redshift population unresolved in both *Spitzer* and HST.

Considering the difficulty of the measurement, we believe the amplitude between NICMOS and *Spitzer* is quite uncertain. We also note that narrow fields such as GOODS and NICMOS UDF are affected by cosmic variance, especially at $z > 6$, where the correlation length of halos responsible for reionization is greater than the field size. These caveats do not rule out the possibility that the *Spitzer* fluctuations, at least at some fractional level, reveal a first-light component. The initial results are clearly exciting and have important implications for galaxy formation, but IR background fluctuations must be further studied at shorter wavelengths, where signatures from reionization are expected to dominate.

CIBER-I

The CIBER instrument currently consists of two wide-field imagers to measure EBL fluctuations, a Low-Resolution Spectrometer (LRS) to probe the EBL via absolute photometry, and a Narrow-Band Spectrometer (NBS) to measure the brightness of the zodiacal by the Ca-II 854.2 Fraunhofer line (Bock et al. 2006). Two imaging cameras operate at 0.9 and 1.6 μm and probe EBL fluctuations over a wide 4 sq. degree field of view, allowing measurements over the distinctive peak in the power spectrum at $\ell \sim 2000$ (0.1 degrees). At the sensitivity of the first flight, CIBER can probe for first-light fluctuations at the level suggested by *Spitzer* measurements at 3.6 μm from Kashlinsky et al. (2007).

With the NBS, CIBER will also test the large EBL intensity (~ 50 nW/m^2 sr) reported by DIRBE and IRTS. The measurement is not limited by the sensitivity of the instruments, but primarily by the zodiacal foreground and to a lesser extent by the astrophysical systematic errors in removing stars and scattered starlight, expected to be $\sim 2\%$ of the zodiacal brightness.

As the residual EBL spectrum closely resembles that of zodiacal light (Dwek et al. 2005), there is the possibility of a large $\sim 25\%$ error in the zodi model used by both DIRBE and IRTS teams. The NBS has sufficient sensitivity and systematic error control to precisely measure the zodiacal amplitude at 854.2 nm. This measurement can be extrapolated to the DIRBE 1.2 and 2.2 μm bands based on the zodiacal spectrum measured by the LRS. We plan to observe multiple lines of sight through the zodiacal cloud, measured over a span of 6 months with 3 more flights, to vary the solar elongation angle. The observation windows are carefully chosen so these fields are within the DIRBE observations at the same time of year. If the DIRBE models are incorrect at the 20% level, this should become readily apparent, and the multiple observations are necessary to help us understand how the zodi models should be corrected.

CIBER-I was first launched from White Sands Missile Range in New Mexico on a Terrier-Black Brant sounding rocket on February 25th, 2009. The vehicle performed as expected, and the payload achieved an apogee of 320 km. Our first science results are expected to be on a first measurement of the EBL between 1 - 2 μm with CIBER and on a fluctuation analysis to test the claims of Kashlinsky et al. (2007) at shorter near-IR wavelengths.

CIBER-II

After four flights with CIBER-I are completed, we plan a more capable camera designed to probe fluctuations down to the low level of minimal reionization fluctuations, with a factor of ~ 10 improvement in sensitivity compared to that of CIBER-I (see Fig. 2). The CIBER-II camera consists of a 30 cm telescope operating simultaneously in four bands between 0.5 and 2.1 μm with each imaging the same 2 sqr. degree field of view. The four bands are matched to identify the spectral dependence of the reionization contribution from foreground and zodiacal fluctuations. As the case with CIBER-I, CIBER-II will image wide fields with existing deep coverage in optical and near-IR with *Spitzer* and ground-based instruments and soon in far-IR with *Herschel*.

The cameras are designed for high sensitivity to surface brightness in the short amount of time available during a sounding rocket flight. In comparison with space-borne telescopes, CIBER-II measures fluctuations on large angular scales, on both sides of the expected peak in the power spectrum. These are also the angular scales best suited for distinguishing this signal from local galaxies and systematic effects due to its distinctive power spectrum. By measuring large angular scales, potential problems with source removal are less serious than in a small deep measurement. CIBER-II is designed to have a very large instrument etendue (a factor of 50 larger than Akari, 100 larger than HST WFC3 and *Spitzer* IRAC), the figure of merit relevant for measuring surface brightness, and so has competitive raw sensitivity even in a short sounding rocket flight compared with the long integrations possible on a satellite. It is expected that CIBER-II will carry out the definitive study to establish the surface density of sources responsible for reionization and its results will complement number counts at $z > 6$ from JWST, especially at the bright end, to assemble a complete picture of reionization.

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